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ALTERNATING-CURRENT POWER DIODE WITH MAGNETIC REGENERATION

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INTRODUCTION

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INTRODUCTION

For generation of electrical power in space directly from a primary source of energy, there are proposed solar cells, fuel cells, thermoelectric converters, radioisotope cells, and thermionic converters; all of these produce direct current. Alternating current can be produced by passing the output of these devices through an inverter such as a solid-state device. At present, the operating temperature for solid-state inverters (~425° K) is sufficiently low so that the accompanying space radiators may prove to be inconveniently large. With the thermionic converter it is possible to produce alternating current directly by several means, one of which is by modulating the plasma diode current with an imposed alternating magnetic field (Ref. 1). The purpose of this study is to show that a self-excited and magnetically controlled diode will produce an alternating current of large amplitude, to find some of the operating characteristics, and to show some of the design considerations of this device.

SYMBOLS

All units are mks unless otherwise noted.

B	magnetic field
C	capacitance
D	emitter diameter
d	thickness of high permeability coil shield
e	electron charge
f	coil-shield factor, Eq. (13)
h	height of diode
I	current (see Fig. 3)
i	current (see Fig. 3)
j	current density
k	Boltzmann constant
L	inductance

n	linear turn density of field coil
P	power
Q	radiant and conductive heat loss
q_o	charge on capacitor in steady-state operation
R	resistance of circuit element
R_L	resistance of control coil
r	internal resistance diode
s	electrode spacing (see Fig. 1)
T	period of oscillation
T_e	emitter temperature
t	time
V	voltage across diode
w	thickness of control coil
β	feedback coefficient
η	efficiency
μ_o	permeability of free space
ρ	resistivity
φ_e	work function of emitter

Subscripts:

a	ac portion of output or circuit
d	dc portion of output or circuit
m	mean value
o	equilibrium value
s	steady operation (constant current with $B = 0$)
u	unsteady operation
1,2	diode 1, diode 2

DIODE CHARACTERISTICS

A sectioned view is shown in Fig. 1 of part of a cylindrical diode. Not shown are the heat source, cesium reservoir, external circuitry, electrode spacers, end structures, etc. The cesium gas is assumed to be ionized either on the hot emitter surface or in the interelectrode space, thus providing ions which tend to neutralize the electron space charge. The decrease in space charge then results in a larger output current and externally delivered power. However, a field coil wound solenoidally around the diode conducts a current which generates the axially directed magnetic field shown on the figure. This field will turn back some of the emitted electrons to the emitter. The amount of the reduction of electron current by the magnetic field will depend on the strength of the field; thus the current in the coil as well as the diode voltage will serve to control the diode current. A set of diode characteristics of this type is shown in Fig. 2, which is reproduced from Fig. 9 of Ref. 2.

Also shown are regions where alternative modes of operation are possible (displayed by the double valuedness of the curves). The arc mode of operation (high currents and low voltages) occurs when avalanche ionization of the cesium takes place in the interelectrode region. The extinguished mode (low currents and high voltages) occurs when ionization occurs chiefly at the emitter surface. The mode actually attained depends on the past history of operation in that as the output voltage is reduced the extinguished mode tends to persist into the double-valued region to some point where the arc is struck (see Ref. 2); the path of the transition in the current voltage plane depends on the external circuitry.

This particular set of data was obtained from a cylindrical diode with a thorium impregnated tungsten emitter at 1800° K, a cesium coated molybdenum collector at 650° K, and a cesium reservoir temperature of 425° K. The electrode spacing was 1 millimeter.

EXTERNAL CIRCUITRY AND ALTERNATING-CURRENT GENERATION

One method of generating alternating current with diodes is by the magnetic coupling of two diodes as shown schematically in Fig. 3, wherein the current through each diode, $I + i$, passes through the field coil of inductance L that controls the other diode; i stands for either i_1 or i_2. The control coil resistances are shown separately as R_L, and R_a is the ac load resistance. The coupling of the circuit to the ac load may be other than a simple resistance, of course, but ideally any load circuit should be designed to react as a pure resistance at the normal frequency, which will be shown to be the natural frequency of the diode circuit loops.

To analyze the circuit of the tandem-diode generator, it is convenient to consider the current loops shown in Fig. 3. The governing equations for loops 1 and 2 are, respectively,

$$V_1 = R_L(I + i_1) + L\, d(I + i_1)/dt + (i_1 - i_2)R_a + \int (i_1/C)dt \qquad (1)$$

$$V_2 = R_L(I + i_2) + L\, d(I + i_2)/dt + (i_2 - i_1)R_a + \int (i_2/C)dt \qquad (2)$$

For the S-shaped loop containing the two diodes, the equation is

$$V_1 + V_2 = (2R_L + R_d)I + (2L + L_d)(dI/dt) + R_L(i_1 + i_2) + L\, d(i_1 + i_2)/dt \qquad (3)$$

The sum and difference of Eqs. (1) and (2) are

$$V_1 + V_2 = 2(L\ d/dt + R_L)I + (L\ d/dt + R_L + \int dt/C)(i_1 + i_2) \qquad (4)$$

$$V_1 - V_2 = (L\ d/dt + 2R_a + R_L + \int dt/C)(i_1 - i_2) \qquad (5)$$

The set of Eqs. (3), (4), and (5) is general, and their numerical solution for specific current-voltage characteristics will be described in a later section. Because of the complex dependence of the diode voltage on the current and magnetic field, the equations are not suitable, without simplification, for stability analysis of the system.

The small oscillation approximation is suitable for investigation of the stability of the circuit. It is assumed that there is a steady-state solution for Eqs. (3), (4), and (5) upon which may be superimposed a small amplitude perturbation. The steady-state condition can be established by temporarily removing the resistor R_a (i.e., $R_a = \infty$) so that the time-dependent currents i_1 and i_2 cannot flow. The voltage V_o and the current I_o of the steady-state are related to the charge q_o on each capacitor by Eq. (3), which now reads

$$V_o = I_o(R_L + R_d/2)$$

and by the equation for the outer loop in Fig. 3,

$$q_o/C = I_o R_d/2$$

When the resistor R_a is replaced in the circuit, the currents i_1 and i_2 will begin to flow as well as, possibly, a perturbation ΔI in the S-shaped loop containing the diodes. The voltages generated by the diodes depend on the currents flowing in them and the magnetic fields impressed on them. To a linear approximation the voltage produced by diode 1 is

$$V_1(I_o + \Delta I + i_1, B_1) = V_o + (\Delta I + i_1)(\partial V_o/\partial I_o) + (\Delta I + i_2)(\partial V_o/\partial B_o)(\partial B_o/\partial I_o)$$

The derivative

$$-(\partial V_o/\partial I_o)_{B_o} \equiv r > 0$$

is the internal resistance of the diode at this equilibrium condition. Similarly,

$$-(\partial V_o/\partial B_o)_{I_o}(\partial B_o/\partial I_o) = -(\partial V_o/\partial B_o)(B_o/I_o) \equiv \beta > 0$$

is the feedback coefficient for the diode. If it is assumed that the magnetic field within the diode can be approximated by that of an infinite solenoid, then

$$(B_o/I_o) = \mu_o n$$

where μ_o is the vacuum permeability and n is the turn density of the control coil. Thus the feedback coefficient depends both on the sensitivity of the diode voltage to the magnetic field and the turn density of the control coil. In terms of the parameters r and β the diode voltages are

$$V_1(I_o + \Delta I + i_1, B_1) = V_o - r(\Delta I + i_1) - \beta(\Delta I + i_2) \tag{6}$$

$$V_2(I_o + \Delta I + i_2, B_2) = V_o - r(\Delta I + i_2) - \beta(\Delta I + i_1) \tag{7}$$

Substitution of Eqs. (6) and (7) into Eq. (5) yields

$$(L\, d/dt - \beta + r + R_L + 2R_a + \int dt/C)(i_1 - i_2)$$

or, as a purely differential equation,

$$\left[L\, d^2/dt^2 + (-\beta + r + R_L + 2R_a)d/dt + 1/C\right](i_1 - i_2) = 0 \tag{8}$$

The current difference $i_1 - i_2$ is the current flowing through the ac load R_a; therefore, examination of Eq. (8) will reveal the growth of ac power in the circuit. The differential operator is that for a harmonic oscillator which predicts growth of the oscillations when the resistive term is negative, i.e., for

$$\beta > r + R_L + 2R_a \tag{9}$$

Thus for the circuit to act as an ac generator, the feedback coefficient must be large enough to overcome the dissipation occuring within the diode and the effective ac load.

The period T of the oscillations is given by

$$2\pi/T = \left\{(1/LC) - \left[(-\beta + r + R_L + 2R_a)/2L\right]^2\right\}^{1/2} \tag{10}$$

and the time in which they grow by a factor e is $2L/(\beta - r - R_L - 2R_a)$. Because the ac power generation depends on $i_1 - i_2$, it is greatest when i_1 and i_2, which are equal in magnitude by symmetry, are of opposite phase. The perturbation ΔI, if it appears initially, damps out with time at a decay rate of $(2R_L + 2r + 2\beta + R_d)/L_d$. The criterion of instability (Eq. (9)) applies only to the initial, or small-amplitude, oscillation. The limiting amplitude is determined by the nonlinear characteristics of the system.

PARTICULAR CASE

To show that alternating current can be generated by the means proposed, and to determine the configuration required to do so, the operational characteristics of a particular design of diode alternator were calculated by using diode characteristics described in Ref. 2. The data from Ref. 2 which seemed suitable for the purposes here were for an emitter temperature of 1900° K, collector temperature of 720° K, and a cesium reservoir temperature of 450° K. The curves for these values of the parameters were fitted with the following expressions:

Arc:

$$j = \frac{\left[2.183 - 0.4308(V + 40B)\right]10^{4}}{1 + \exp\left[5(V + 40B - 1.126)\right]} \tag{11}$$

Extinguished:

$$j = \frac{1.615\times10^{4}}{\left[1 + (158B)^{2}\right]\left\{1 + \exp\left[5(V - 1.508)\right]\right\}} \tag{12}$$

where B is in webers per square meter, V is in volts, and j is in amperes per square meter. It is not clear in Ref. 2 whether the low voltage region for these particular characteristics is one of double-valued currents, such as it is for the characteristics shown in Fig. 2. The calculations made by using Eqs. (11) and (12) were nevertheless programmed to include the possibility of such a region, but no operating points were found there. Thus, for the present purpose these curves may be regarded as single valued, and for a given voltage and magnetic field, the larger of the currents from Eq. (11) and (12) may be used. After selecting these characteristics from Ref. 2 the values of the other diode parameters were assigned. The selected values (see Fig. 1) were an emitter diameter D of 4 centimeters, a height h of 16 centimeters, a copper field coil of thickness $w = 1.0$ centimeter, (assumed to be operating at a temperature of 500° C), and a high permeability cylindrical coil shield of thickness $d = 0.3$ centimeter (assumed to halve the reluctance of the magnetic circuit). The field-coil turn density n was chosen at 75 turns per meter by trial and error, in order to provide sufficient feedback to maximize the usable ac power with consideration of the field-coil losses. For these conditions, $L = 2.36\times10^{-6}$ henry and $R_L = 0.7\times10^{-3}$ ohm.

Optimum power output was achieved with a dc load per diode $(R_L + R_d/2)$, and an ac load $(R_L + 2R_a)$ each equal to 4.5×10^{-3} ohm, which is the value for maximum power with constant diode current and zero magnetic field. At the mean operating point determined by the foregoing load resistance and coil inductance, the feedback factor β and internal diode resistance r are approximately 7.5×10^{-3} and 2.5×10^{-3} ohm, respectively. Frequency of oscillation was adjusted by means of the capacitors shown in Fig. 3.

Numerical solutions of the general circuit Eqs. (3), (4), and (5) supplemented by the diode characteristics (Eqs. (11) and (12)) are shown in Figs. 4 to 6 for three different operating frequencies. Paths of operation in the voltage-current plane are shown by curves in Figs. 4(a), 5(a), and 6(a); arrows indicate succession of operating states. Generally, these curves are open figures with one crossing point. They show the presence of substantial even harmonics by the arching and by the double-loop characteristic. Moreover, the even harmonics, when large, produce an accompanying steady current that shifts the mean operating point from its position on the load line for linear oscillations. Despite the presence of these nonlinear effects, the base frequency is very close to that predicted by linearized theory (Eq. (10)).

The corresponding time plots of voltage and current shown in Figs. 4(b), 5(b), and 6(b). The current is seen to be more nearly sinusoidal than the voltage curve, which exhibits the appearance of large harmonic components. Particularly noticeable are the voltage spikes near the current minimum where transition from the arc to the extinguished mode occurs. This spike reduces the ac power output because the ac component of current is negative at the same time. At low frequency (Fig. 6(b)) the ac power output (47.4 w) is larger than that at high frequency (29.5 w, Fig. 4(b)) because the form of the current variation is closer to a square wave. Calculated values of the ratio of ac to dc power (P_a/P_d) were 0.70 at low frequency and 0.47 at high frequency. This ratio depends on the current and voltage waveforms, and the degree of modulation of the current by the magnetic field; for a fully modulated sine wave or square wave, the power ratio has values of 0.5 and 1.0, respectively, as shown in the next section.

The total power output of the diodes depends on the scale of the device; therefore, the ac and dc power outputs for the cases calculated here are given in table I as ratios to the maximum steady-state ($B = 0$) power output P_s of the diodes. The scale of the device assumed corresponds to $P_s = 322$ watts per diode. These data confirm that an advantage can be achieved in both ac and dc power if the external circuit is designed to achieve an approximation to a square wave current.

For a given total load resistance the ac power increases rapidly with turn density from zero, for a value of n such that $\beta = r + 2R_a + R_L$, to the power at nearly maximum current amplitude; a further increase in n merely increases the coil loss. For example, of two cases with

$R_L + 2R_a = 4.5 \times 10^{-3}$ ohm, the one with an n of 72.5 turns per meter developed an ac current amplitude of 150 amperes, while the other developed an ac current amplitude of 230 amperes when n was increased to 75 turns per meter. The control-coil losses are arbitrary in that they depend directly on how much metal one is willing to use; for the dimensions assumed in the present case, the losses were approximately 16 percent of the diode output.

SOME DESIGN CONSIDERATIONS

Scaling

The results described thus far are limited to a diode of specific size and proportion. The question arises as to what is the effect of size on the generator characteristics. Similar operating conditions interior to different sized diodes are expected for the same electrode materials, emitter, collector, and cesium reservoir temperatures, spacing, current density, magnetic field, and voltage. Then since $I = j\pi Dh$, the resistance at the diode terminals is

$$R_L + \frac{R_d}{2} = R_L + 2R_a = \frac{V}{I} = \frac{V}{j\pi Dh}$$

Thus larger diodes would require smaller resistances varying as $1/hD$. The required magnetic field B is approximately $nI\mu_o f$, where f is the factor resulting from the use of the high permeability shell to surround the field coils. The field coil resistance is then

$$R_L = \frac{\rho\pi(D + w)nh}{w\,\frac{1}{n}} = \frac{\rho}{\pi}\left(\frac{B}{\mu_o fj}\right)^2 \frac{1}{hD}\left(\frac{1}{D} + \frac{1}{w}\right) \qquad (13)$$

where ρ is the resistivity of the coils. Thus, the ratio of control coil loss to total power $R_L/(R_L + 2R_a)$ varies as $1/D + 1/w$. That is, the control coil is relatively more efficient for larger diodes and thicker control coils, although other losses, such as heat radiation and conduction, may be more important.

Power Consumption and Output

A comparison of unsteady diode operation with steady operation (no magnetic field) will show a reduction of power and efficiency which may be compared with the reduction other methods of conversion of dc to ac power. For the purpose of estimating the heat input to the emitter, it is convenient to consider that this heat will be used partly in electron emission, partly in heat losses (Q) which include conduction through the leads and structure, and also by radiation. The first part is therefore, proportional to the net current, which consists of that fraction of emitted electrons having sufficient energy to surmount the maximum potential barrier within the diode V_b. (Currents resulting from volume ionization are assumed negligible.) Since the barrier voltage in arc mode is the potential on the emitter surface, each electron removes the energy $e\varphi_e$ and the average kinetic energy $2kT_e$ where φ_e is the emitter work function, e the electron charge, k is Boltzmann's constant, and T_e the emitter temperature. Thus, for steady-state operation the electron cooling loss is $I_s(\varphi_e + 2kT_e/e)$; whereas for unsteady operation the electron cooling is $(I_u + i)(\varphi_e + 2kT_e/e)$. This power varies from zero to $I_s(\varphi_e + 2kT_e/e)$. The average electron cooling loss per cycle depends in general on the waveform of the diode output current; for the most useful waveforms, including fully modulated sinusoidal and square waves, the average current and corresponding loss are approximately one-half the steady-state values. The heat Q does not vary with the current, so that $Q_u \sim Q_s \equiv Q$. Emitter power consumption is then $Q + I_s(\varphi_e + 2kT_e/e)$ for steady-state and $Q + I_s(\varphi_e + 2kT_e/e)/2$ for oscillatory operation. The heat loss by conduction and radiation is thereby seen to be relatively more important when producing alternating current than when producing direct current.

The power output P_s in steady operation is

$$P_s = I_s V_s$$

In unsteady operation there is a dc component of power depending on the mean voltage and current

$$P_{\cancel{s}d} = V_m I_m = \frac{1}{4} V_s I_s = \frac{1}{4} P_s$$

and an ac component P_a, the value of which depends on current and voltage oscillation amplitude, waveform, and phase shift. For a fully modulated square wave with no phase shift,

$$P_a = \frac{1}{4} P_s$$

$$P_u = \frac{1}{2} P_s$$

and for a sine wave

$$P_a = \frac{1}{8} P_s$$

$$P_u = \frac{3}{8} P_s$$

(see Fig. 7).

The efficiency is then related to the steady-state value by

$$\eta_u = \frac{P_u}{P_s} \frac{P_s}{\frac{1}{2} I_s(\varphi_e + 2kT_e/e) + Q} = \eta_s \frac{P_u}{P_s} \frac{Q + I_s(\varphi_e + 2kT_e/e)}{Q + I_s(\varphi_e + 2kT_e/e)/2}$$

This equation indicates that the ac efficiency of a diode will be closer to the dc value if the radiation and conduction loss is small compared with the electron cooling loss. If we assume as an attainable diode design one in which the heat loss by radiation and conduction is one-half the steady-state electron cooling loss, then for a square wave $\eta_u/\eta_s = 0.75$, and for a sine wave $\eta_u/\eta_s = 0.56$.

CONCLUDING REMARKS

In view of the simplicity and relatively elevated minimum system temperature of the self-excited ac generating diode and circuit, a complete system analysis might well establish that the inefficiency is tolerable for some space power applications.

The penalty in efficiency that arises from use of the plasma diode in the proposed ac power-generating circuit is the result of the part-time power production by the diode, while radiation and conduction heat losses continue as in dc operation. High efficiency diodes with small conduction and radiation losses would be most suitable for this intermittant use.

Some improvement by reduction in size of the field coil and elimination of the high permeability field-coil shield might be achieved by optimization of electrode spacing and cesium vapor density to obtain an increased sensitivity to the magnetic field.

Another feature of ac power generation by magnetic control of a diode output is the continued production of a dc component of power, which is at least as great as the ac component. This diode oscillator is, therefore, better suited for application to situations in which both the dc power and the ac power can be used.

REFERENCES

1. Schock, Alfred: Effect of Magnetic Fields on Thermionic Generators. Jour. Appl. Phys., vol. 31, no. 11, Nov. 1960, pp. 1978-1987.

2. Schock, A., Eaton, W. E., Eisen, C. L., and Wolk, B.: Magnetic Field Effects in Thermionic Plasma Diodes. Advanced Energy Conversion, vol. 3, no. 3, July-Sept. 1963, pp. 537-549.

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TABLE I. - POWER OUTPUTS

Frequency, cps	Figure	P_a/P_s, percent	P_d/P_s, percent	$(P_a + P_d)/P_s$, percent
120	6	15	21	36
10^3	4	9	19	28
10^4	5	10	19	29

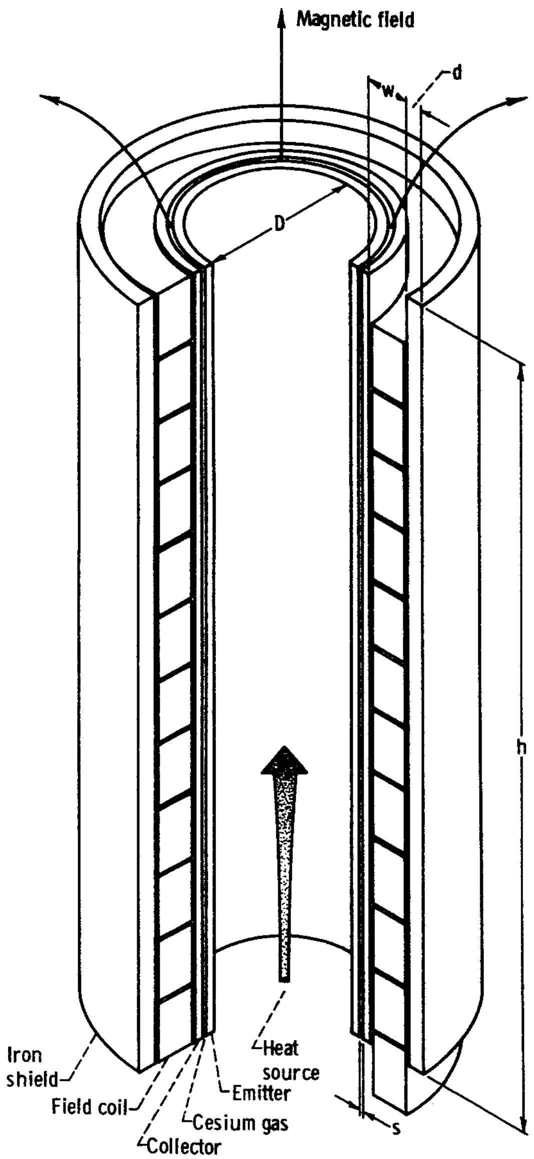


Figure 1. - Diode and field-coil configuration.

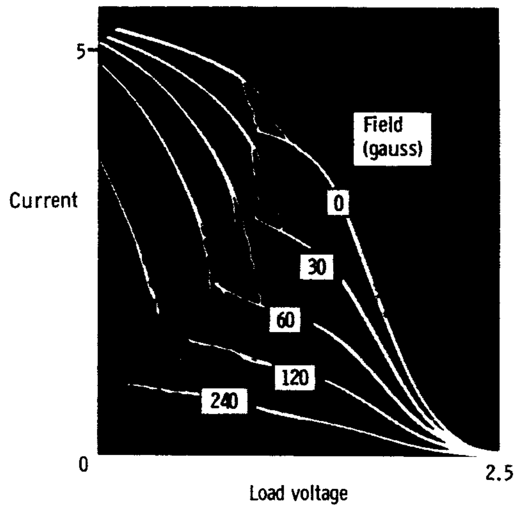


Figure 2. - Arc and glow modes of diode operation.

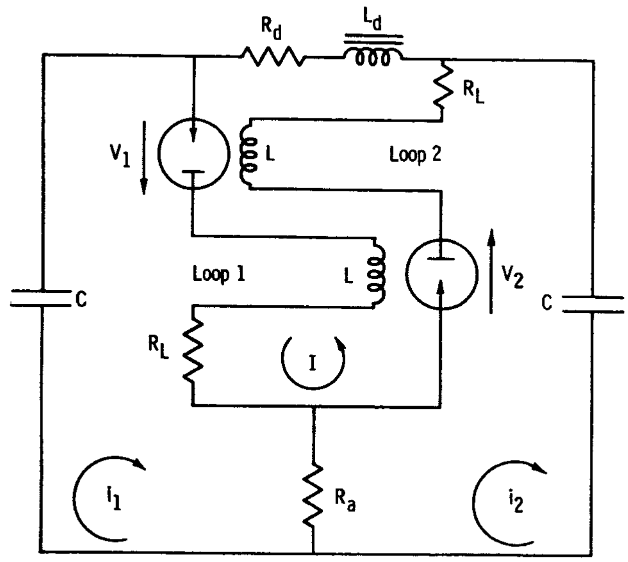
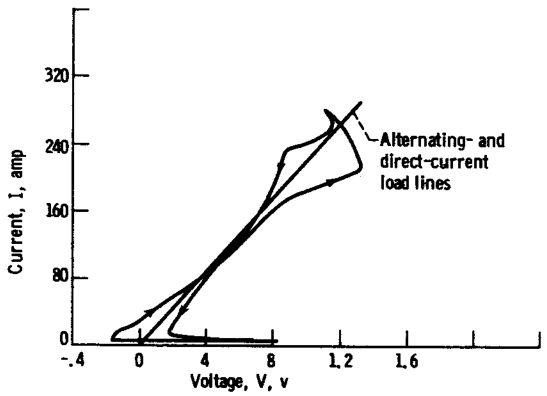
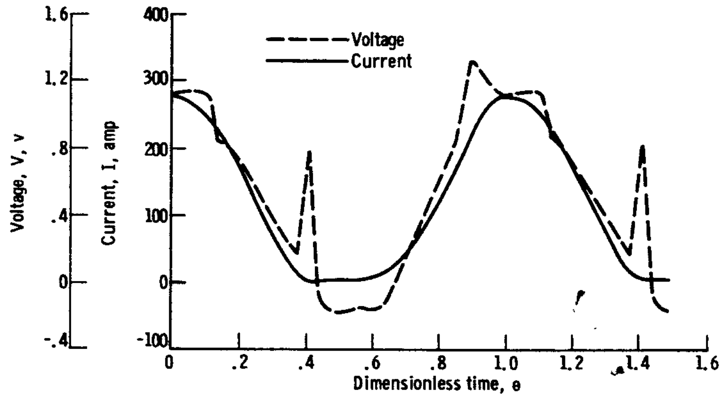


Figure 3. - Tandem-diode generator circuit.



(a) Voltage - current diagram.



(b) Time variation of voltage and current.

Figure 6. - Generator operation at 120 cps. Linear turn density, 75 turns per meter; $R + 2R_a = R + R_d/2$, 0.0045 ohm.

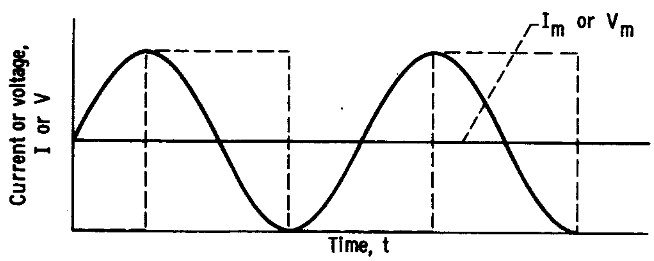


Figure 7. - Current and voltage components for either sinusoidal or square wave output.